Semi-autonomous Rover Operations: An Integrated Hardware and Software Approach for More Capable Mars Rover Missions

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***Abstract*—The SRO project is using the 25 kg solar powered SR2 rover to explore rover solutions for long distance Mars missions. The SR2 rover is autonomous rover prototype that has been involved in a number of extended field tests involving Mars-like terrain. The four-wheeled rover uses only two motors for mobility (versus the 10+ used on the Pathfinder and MER rovers). Despite the drastic reduction in actuators, the mobility of SR2 is, by most measures, comparable to that of the rocker-bogie designs. The few areas where it is less capable can almost always be overcome by following some simple rules which have been incorporated into the robot's software. The reduction in actuators greatly simplifies the onboard real-time software, and can simplify operations as well. During the majority of any traverse, when the robot is on relatively clear ground, the SR2 system is much more power efficient than a rocker-bogie, again improving range and simplifying operations.**

The real-time software likewise is following a simplified, highly reactive approach. The rover is left on its own to make its way between way-points that are spaced, on average, about 50 m apart. The rover is given 10s of way-points to cover on its own between communication cycles. While the path followed by the robot between way-points may not be as optimal as one planned out on the ground, the increased time spent actually roving more than makes up for this. In tests at the Tule Wash field site (near Salton Sea, California), the rover would regularly make 300m/hr of progress toward the goal (the actual distance traveled, with detours, might have been 20% longer), allowing distances on the order of a km/day easily reachable.

This rover capability enables a lower cost mission architecture that provides access to specific points on the surface of Mars.

I. Motivation

The Mars we know today is very different than the Mars understood just 10 years ago. Detailed observations from Mars Global Surveyor (MGS), Mars Odyssey and Mars Reconnaissance Orbiter (MRO) show that the planets geology is quite diverse. Mars Orbiter Camera (MOC) and Thermal Emission Imaging System (THEMIS) results, in particular, underscore this diversity [1],[2]. Much of the story is recorded in sedimentary rocks and deposits; major discoveries have centered on evidence for the work of liquid water (Figure 1), including sediment transport in recent polar and mid-latitude gullies [1], [3], and a record of early Mars preserved in sedimentary rocks [4], [1], [5]. Documentation of evidence for processes that involved liquid water requires the study of sediments. Thousands of locations across Mars exhibit sedimentary rocks, and >1300 gully sites (and >14,000 individual gullies) have been identified [6]. While it is not feasible to study all of these sites with landers, rovers, or sample return missions, it is unrealistic to expect to understand the role of water in martian geologic history without surface study of many more sites than currently planned within the Mars Exploration Program (MEP).

Determining the origins of both martian sedimentary rocks and gullies will include the application of 300+ years of traditional field geology and sedimentological research. A crucial aspect of field geology involves inspecting and sampling the right outcrops, where the relationships between layers and the structures and textures within individual layers are accessible to imaging and sampling. The Mars Orbiter Camera (MOC) on Mars Global Surveyor (MGS) and the High Resolution Imaging Science Experiment [7] on the Mars Reconnaissance Orbiter (MRO) provide us with the equivalent of a key tool of the modern field geologist: aerial photography. Overhead high resolution imaging allows identification of candidate right outcrops during the planning stages of a mission, so we can know exactly where we need to go to within a meter.

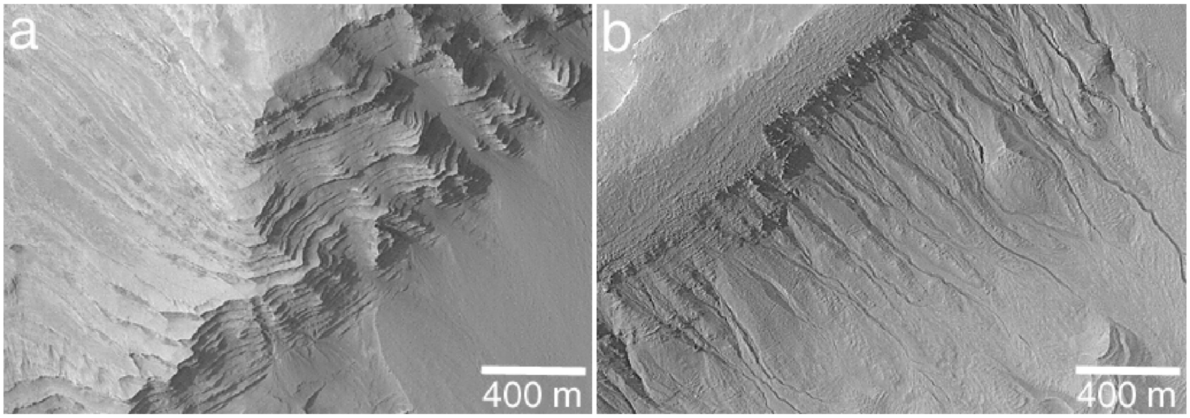

Fig. 1. Science Motivation: (a) Layers of possible water-lain sediments, representing the record of early Mars, in Terby Crater, MOC image R06-00037. (b) Geologically young gullies in a crater in Newton Basin, MOC image R06-00688.

Unfortunately, current and planned rovers can't get there in a cost effective fashion. The Mars Exploration Rover (MER) system, while having traveled more than an order of magnitude further than in its original mission profile[1], is not capable of reaching specific outcrops designated prior to landing (due to the size of the landing ellipse) within a timely manner. While current plans for the Mars Science Laboratory (MSL) rover do have the range of a scale comparable to the landing accuracy, the apparent cost of that system will prohibit its use for any more than a few sites. Study of many sites, as will no doubt be necessary to answer critical questions about water and life on Mars, will require a less expensive system.

A niche for a small, solar powered, autonomous, long range rover is created by the following factors:

- Landing errors on Mars will likely remain in kilometers to tens of kilometers for the foreseeable future, at least for Mars Scout-class missions.
- High resolution imaging of the surface, from MGS MOC and from the high resolution instruments on MRO, allow us to both:
  - Pose important scientific questions that can only be addressed by making measurements at specific locations, and
  - Plan traverses to those specific locations avoiding the larger scale (meters to kilometers in scale) obstacles visible in orbital imagery.
- Existing and planned relay assets at Mars provide communication to surface vehicles at comparatively low mass, power and complexity (compared to a direct to Earth link), but at the operational cost of less frequent contacts.
- Rover experiments performed by MSSS and OU demonstrated that it is feasible for a 20-30 kg surface vehicle to autonomously traverse long distances by moving between waypoints fifty to hundreds of meters apart, at speeds of order 300 m per hour, over surfaces similar to those found on Mars, using solar power.

Taken together, these factors define an opportunity, not exploited by the current MEP, to address key issues in Mars science in the context of less expensive Mars Scout missions. Such rovers could be substantially simpler, lighter and cheaper than the MER rovers, less labor intensive to operate, while still providing a scientific capability that could not be provided by the MER rovers.

For the 2011 Mars Scout opportunity, MSSS proposed a mission to put two landers on Mars (one at a sedimentary layer site, the other at a gully site), each with two rovers. Each 60 kg rover carried about 10 kg of science payload, and could drive itself 1-2 km per day for up to month to reach the field site. Communications with the rovers was via the orbital relays, and assumed to occur once a day. Between these limited, daily communications windows, each rover would be operated autonomously, its traverse constrained by waypoints provided by the ground. Besides the substantial mass and power savings on the rover by eliminating the direct to Earth link, an ancillary benefit of this limited communication window is that it can be supported by an operations tempo substantially less frenetic than required for a rover with a direct-to-Earth link. Because of power constraints, little science would be done on the traverse. The compliment of this is that comparatively little traversing would be done once the field site had been reached, and most of the power could be devoted to science.

[1]As of this writing, Opportunity has traveled 10, 736m in 1163 Sols [8]

Fig. 2. The SR2 rover during a May 2007 field test in the Anzo Borrego desert.

II. The SR2 Rover

The SR2 rover (Figure 2) is a 25kg Mars rover testbed designed to test long range reactive navigation is realistic terrain situations. The rover has four wheels, is differentially steered, and uses only two motors for mobility. The motors are located in the chassis and the wheels are driven through a power train consisting of two gearboxes and drive shafts (see Figure 3). The specific mechanics of the suspension and drive-train are described in [9], [10] and most thoroughly in [11].

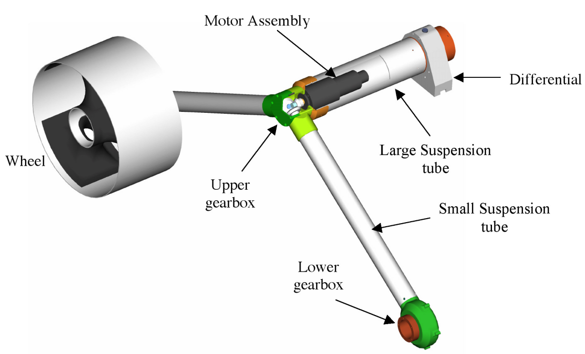

Fig. 3. One side of the SR2 drive train. The body and wheel have been removed for clarity.

The rover has gone through a number of field tests – whose results lead to modifications to the rover and further field tests. In particular, the rover has gone through several versions of wheels. The initial wheel system used rigid, flat, open wheels to minimize rolling resistance and allow the soil to flow through the wheels during skid turns [12]. The current version uses closed (to avoid getting caught on rock outcrops), curved wheels (to improve buoyancy and traction in soft soil) with compliant hubs (to relieve stress on the suspension and reduce chance of wheel entrapment during skid turns) [13]. The current wheels are shown in Figure 4.

Fig. 4. The tension spring wheel provides a compliant hub to absorb shock and allow wheel deflection during skid turns. Wheel grousers are not shown.

The rover is outfitted with heading, roll and pitch sensors and two small scanning laser range sensors (maximum range is less than 4m). The rover carries a GPS and a high resolution stereo camera mounted on a pan and tilt head. The GPS and cameras are payload, and their data is not used in rover navigation (though it is used in analyzing the rover's performance).

The rover is equipped with a 75 watt solar panel and a LiIon battery system. The battery is capable of running the rover for approximately one hour. In the 2007 field test configuration the rover would operate for five to six hours per day; performing about 40 minutes of science (taking a 64 image stereo mosaic of its surroundings) and spending the remainder of the time roving or charging.

III. Rover Capabilities

The SR2 rover exhibits, in most cases, mobility similar to that of a rocker-bogie system. Like a rocker-bogie [14], SR2 can climb obstacles well in excess of a wheel diameter. The differential between the two sides of the vehicle on both the SR2 and the rocker-bogie keep the wheel load balanced and ensure good wheel contact with the surface, even in uneven terrain. Both systems have the body mounted on the differential, allowing large ground clearance. Because SR2 has only four wheels, its step climbing performance is not as good as a rocker-bogie. However, steps seldom occur in natural terrain, and even when they are encountered, by approaching the step at an angle, rather than straight on, SR2 is easily able to climb steps, one wheel at a time.

The SR2 robot was tested in Mars-like terrain at Tule Wash in the Anza Borrego Desert on the western margin of the Salton Sea in Southern California. This site was selected because of its high fidelity as an analog to the most easily accessible of the layered, sedimentary materials on Mars. As on Mars, the topography is relatively low, with well-isolated vehicle-scale non-traversable terrain elements (escarpments, deep channels, etc.) and a relative paucity of large rocks. On Mars, this configuration of terrain elements arises from the nature of the layered rocks: lithified wind or lake-water lain sediments, cemented to the extent they can maintain small ($<$10 m), steep (up to 90^o) stepped topography but weak enough that material shed from such topographic steps quickly breaks down to wind-transportable scale. The absence of impact craters leads directly to the paucity of rocks. The Borrego site is similarly situated on water lain sediments eroded by transgression of a lake and by ephemeral fluvial processes. The absence of large boulders, as on Mars, reflects the absence of processes to create such boulders.

We have conducted over 10km of autonomous traverses in this test area. These traverses have been along paths with way-points chosen using meter-scale satellite imagery, before going out into the field, as would be the case with actual flight operations. The way-points are typically spaced between 10 and 100m apart, and are chosen to avoid terrain hazards that can be seen from orbit. Local navigation of rocks, holes, and small ridges (0.5m and smaller) are left to the rover's onboard navigation system.

Fig. 5. After traveling a number of meters along the ridge, SR2 finds an easy location to climb over.

In both circular and linear traverses of many hundreds of meters, the rover is able to maintain dead-reckoning accuracy of approximately 2 to 3% of distance traveled (Figure 6). While this is much better than the norm, this means that after a half kilometer traverse the rover may be off the prescribed path by 10 or 15 meters. In some situations this means that the rover might miss a narrow pass through a ridge designated in the path. The rover must then be able to find its own way along a ridgeline (Figure 5) or be able to determine when it is stuck and call home for help.

The current system is able to find its way or notice when it is stuck with one exception: sandy slopes. The current wheels on SR2 (and on other rovers such as MER) do not provide good performance in loose sand, especially when climbing up a slope. Since the rover's position is determined (internally) by heading and wheel odometry information, sandy slopes can cause massive dead reckoning errors.

We are continuing our wheel design work in an attempt to find a wheel that performs well on both sandy and solid terrain. We are also exploring techniques such as the integration of visual odometry which will provide better information to the rover about its progress over the surface than wheel odometry alone.

IV. Conclusions

Mars science dictates the need for rover traverses at speeds and distances one to two orders of magnitude greater than is currently being flown. Because of the hazardous terrain that these missions will be exploring, it makes sense to use multiple, lower-cost, rovers to carry out these missions. The SRO task and SR2 rover have shown that larger spacing of way-points, reduced communication between the ground and rover and simplified rover mechanics and navigation is all possible – and produces very promising results. Additional work, for all rovers, is needed to handle sandy slopes more successfully.

Acknowlegments

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Fig. 6. Traverse data from a 2006 field test of the SR2 rover. The planned path is in grey as is almost exactly overwritten by the GPS data of the rover's actual traverse. A significant deviation from the planned path occurred one day when the wrong initialization file was loaded onto the rover, with an incorrect magnetic declination. The rover was given its actual location at the start of each day's run.

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